Lepton number violation search with neutrinoless double beta decay: overview over experiments

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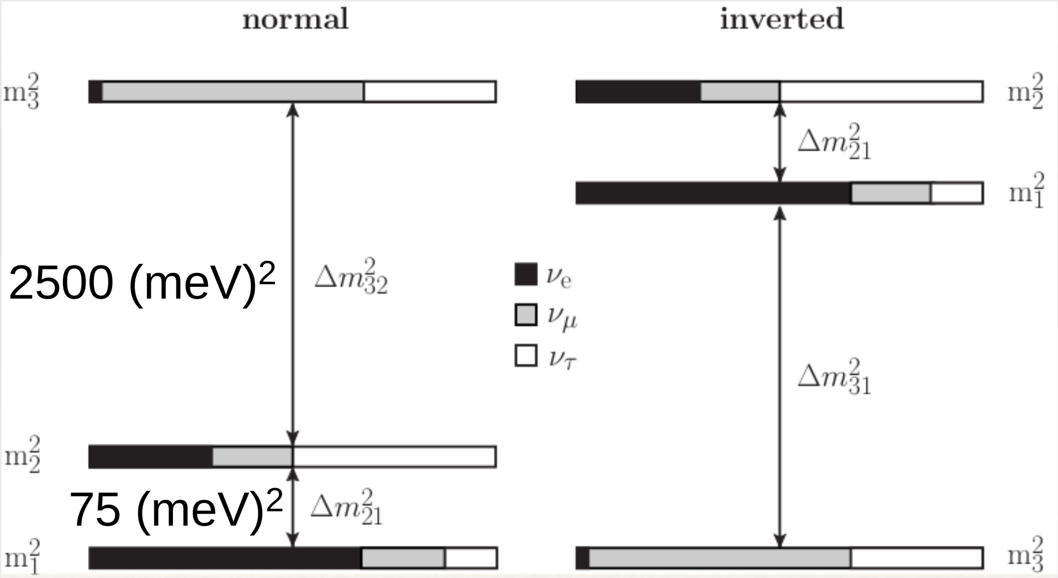
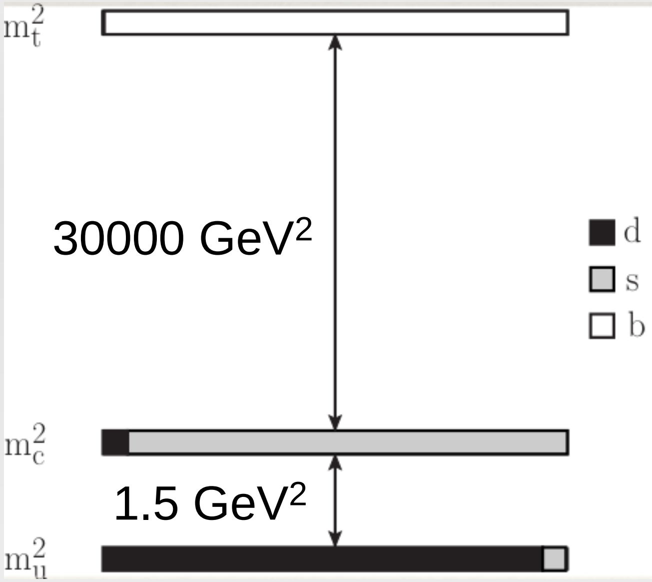
disclaimer: I will only discuss experiments with new results in this talk

Topics in neutrino physics

neutrinos: mass splitting and mixing



quarks



Neutrino flavor physics: underlying symmetry ?

- mixing matrix U and $|\Delta m^2|$, quite well known but: $\theta_{23} = 45^o$ or small deviation from 45^o ?
- sign of Δm_{31}^2 ?
- CP phase = $3\pi/2$? (likely not relevant for leptogenesis)

Neutrino mass: absolute mass scale, origin of neutrino mass: why are masses so small ?

major impact {

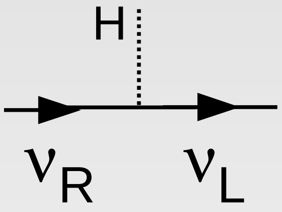
Is mixing matrix unitary (sterile neutrinos, ...)?

Are neutrinos Majorana or Dirac particles (lepton number violation)?

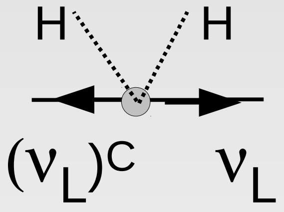
Neutrino mass: Lepton number violation?

possible neutrino mass terms (ν has no electric charge)

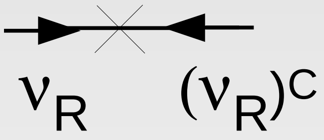
$$L_{Yuk} = m_D \bar{\nu}_L \nu_R + m_L \bar{\nu}_L (\nu_L)^C + m_R (\bar{\nu}_R)^C \nu_R + h.c.$$



$\Delta L=0$



$\Delta L=2$



$\Delta L=2$

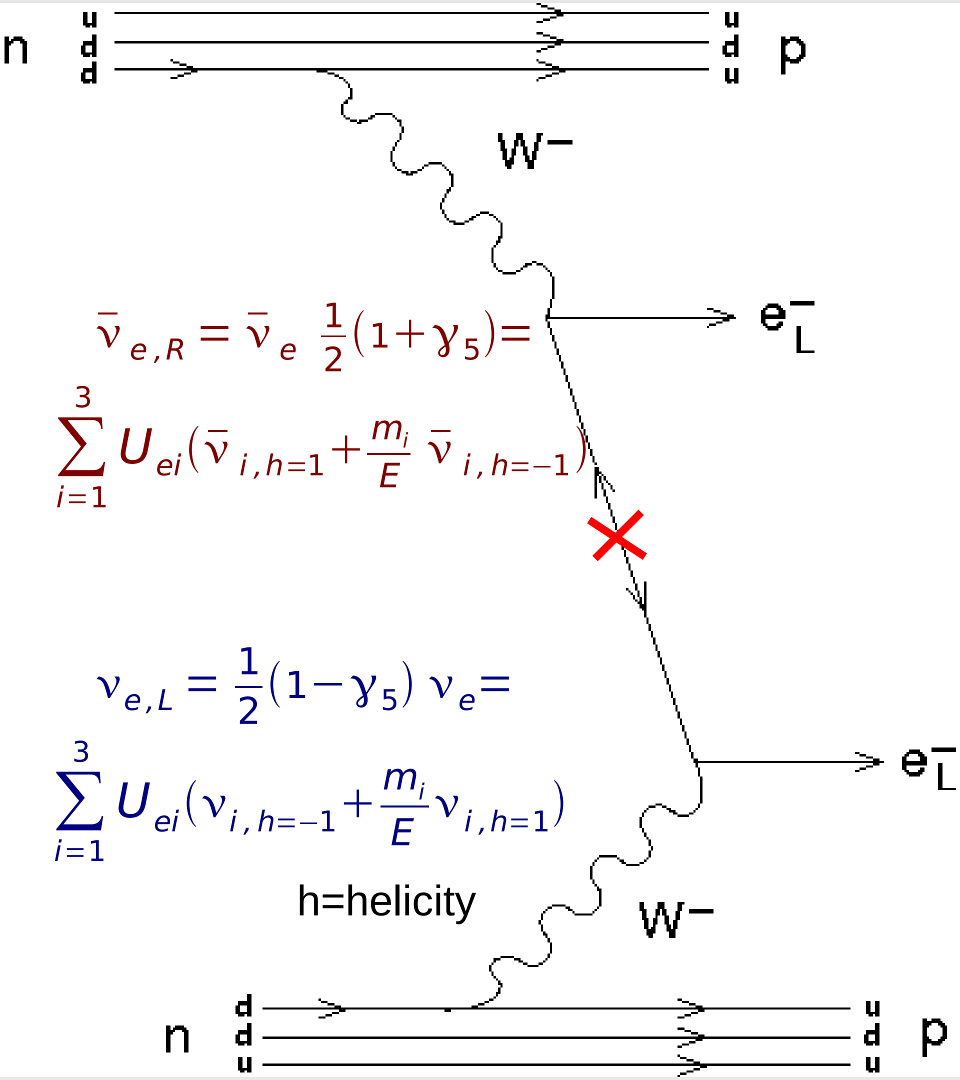
eigen vector $N \sim \nu_R + (\nu_R)^C$ $\nu \sim \nu_L + (\nu_L)^C$ Majorana particles

mass ($m_L \sim 0$) m_R m_D^2 / m_R

in general: expect ν to be Majorana particles → L violation

How to observe ΔL=2: 0νββ

Look for a process which can only occur if neutrino is Majorana particle



$$\bar{\nu}_{e,R} = \bar{\nu}_e \, \frac{1}{2}(1+\gamma_5) = \sum_{i=1}^{3} U_{ei}\left(\bar{\nu}_{i,h=1} + \frac{m_i}{E}\,\bar{\nu}_{i,h=-1}\right)$$

$$\nu_{e,L} = \frac{1}{2}(1-\gamma_5)\,\nu_e = \sum_{i=1}^{3} U_{ei}\left(\nu_{i,h=-1} + \frac{m_i}{E}\nu_{i,h=1}\right)$$

h=helicity

coupling strength ~ $m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2 m_i$

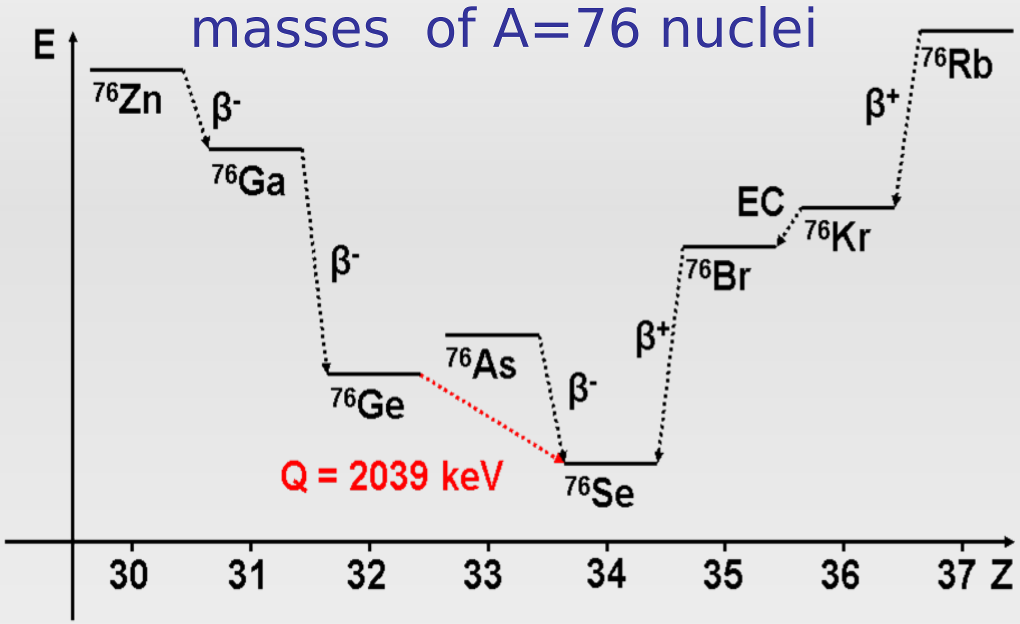
function of
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

also possible: heavy N exchange

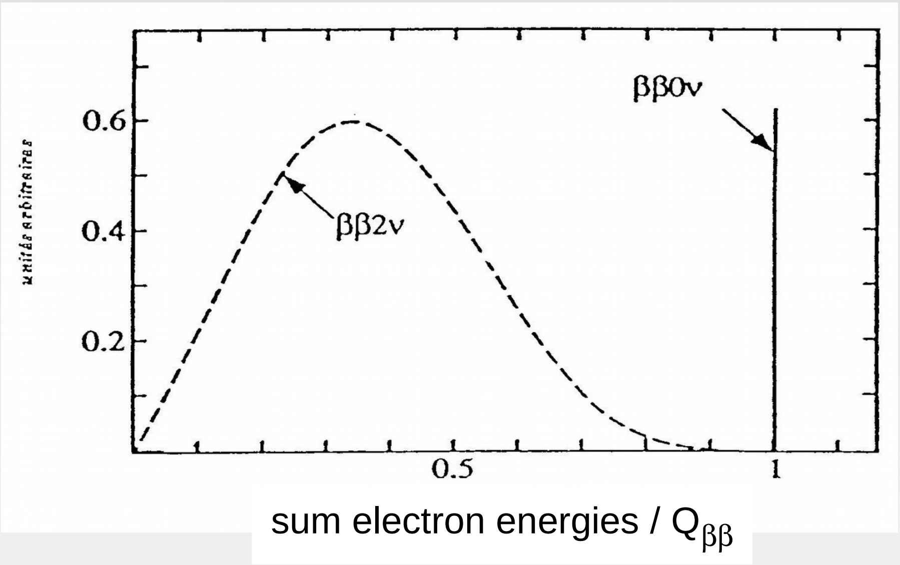
→ coupling strength ~ $\sum_{i=1}^{3} V_{ei}^2 / M_i$

Neutrinoless double beta decay

masses of A=76 nuclei



experimental signature for ββ



"single" beta decay not allowed

$\longrightarrow$ only "double beta decay"

$(A,Z) \longrightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}$ $\Delta L=0$

$(A,Z) \longrightarrow (A,Z+2) + 2\,e^-$ $\Delta L=2$

Note: similar process in principle also observable at accelerator or reactor or ... but for light Majorana neutrino:

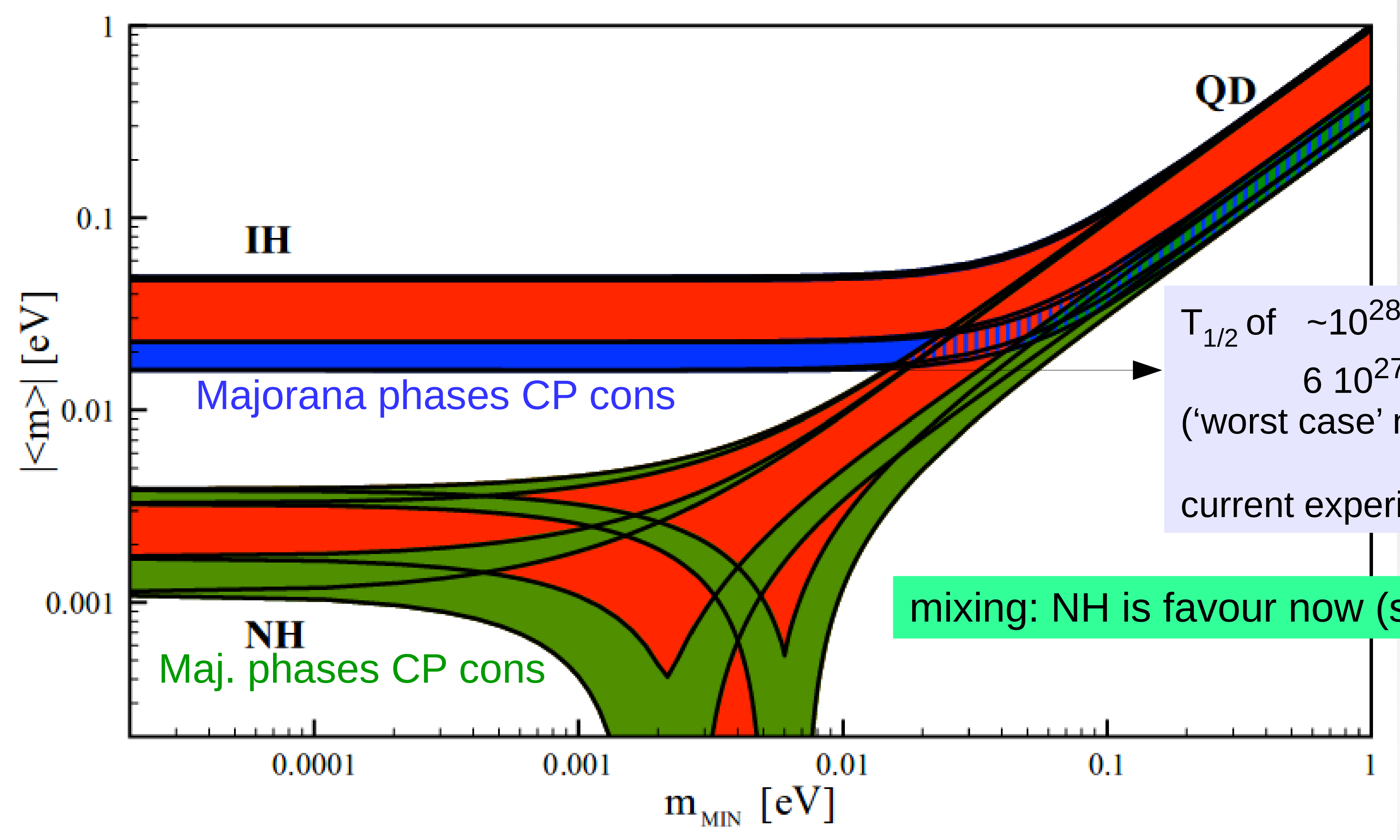
- background too high
- flux too low compared to Avogadro N_A

0νββ: search for a line at Q value of decay

Light Majorana neutrino exchange

scan of $m_{\beta\beta}$ (Δm_{atm}^2, Δm_{sol}^2, m_{min}, θ_{atm}, θ_{sol}, θ_{13}, 2 Majorana phases)

according to measurements (2 σ range) or random (2 Maj. phases)



Majorana phases CP cons

Maj. phases CP cons

$T_{1/2}$ of ~10^{28} yr for ^{76}Ge

$6\ 10^{27}$ yr for ^{136}Xe

('worst case' nuclear matrix element)

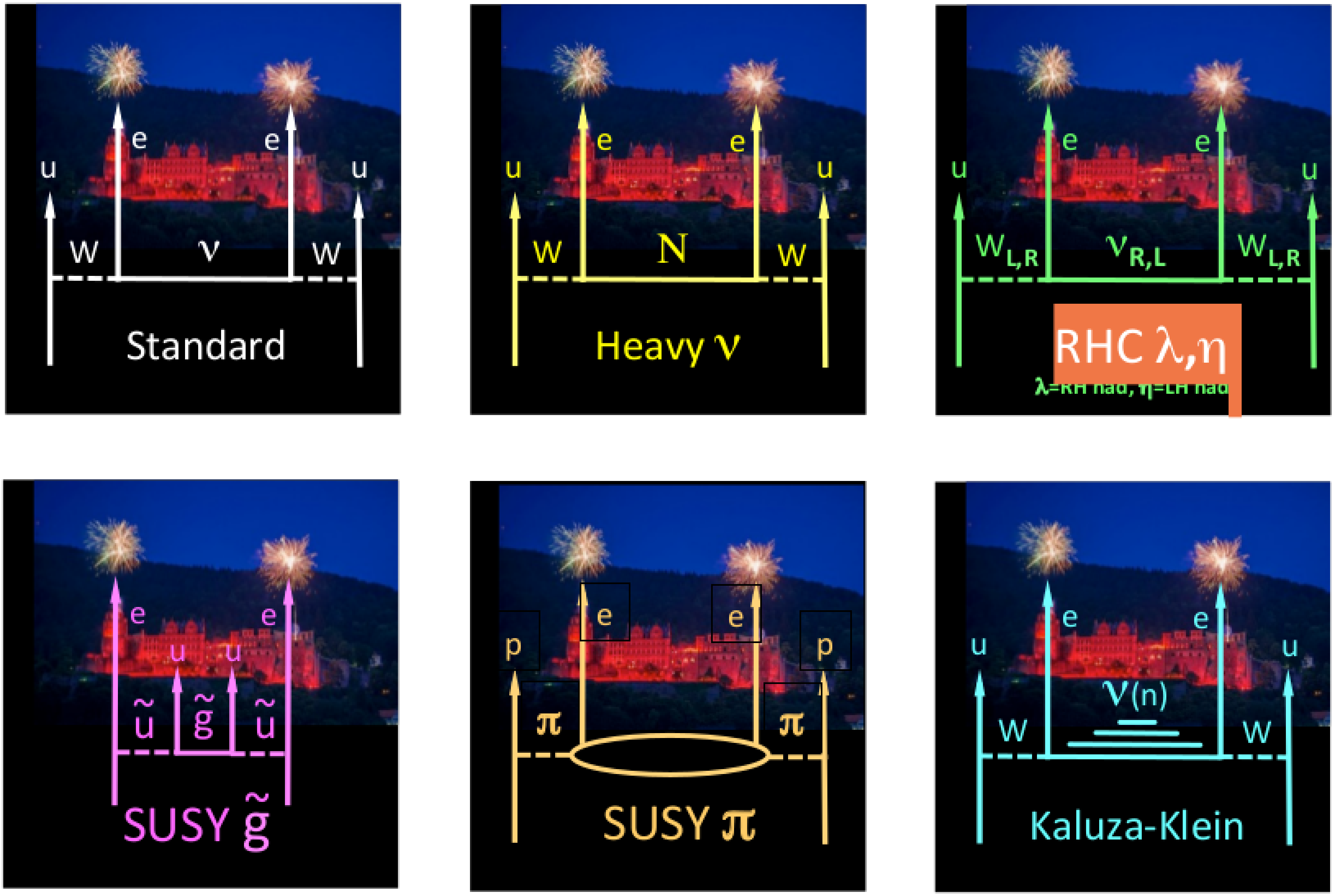
current experiments 10^{25} - 10^{26} yr

mixing: NH is favour now (see Neutrino18)

PDG 2016

$0\nu\beta\beta$: other mechanisms

Warning: **don't stick to $m_{\beta\beta}$ metric, just go on with $T_{1/2}$!** Variety of $0\nu\beta\beta$ mechanisms:



$0\nu\beta\beta$ from any mechanism → **Majorana nature of ν would be established anyway**

ΔL & new physics also at LHC, LFV

Lisi: Neutrino18

From $T_{1/2}$ to $m_{\beta\beta}$

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}\left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$T^{0\nu}_{1/2}$ = measured experimentally

$G^{0\nu}$ = phase space factor ~ Q^5

$M^{0\nu}$ = nuclear matrix element

m_e = electron mass

need $M^{0\nu}$ to understand physics mechanism

selected 0νββ isotopes from PRD 83 (2011) 113010

Isotope	$G^{0\nu}$ [10^{-14}y]	Q[keV]	nat. abund.[%]
^{48}Ca	2.5	4273.7	0.187
^{76}Ge	0.23	2039.1	7.8
^{82}Se	1.0	2995.5	9.2
^{100}Mo	1.6	3035.0	9.6
^{130}Te	1.4	2530.3	34.5
^{136}Xe	1.5	2461.9	8.9
^{150}Nd	6.6	3367.3	5.6

enrichment required except for ^{130}Te,
not (yet) possible for all, costs differ

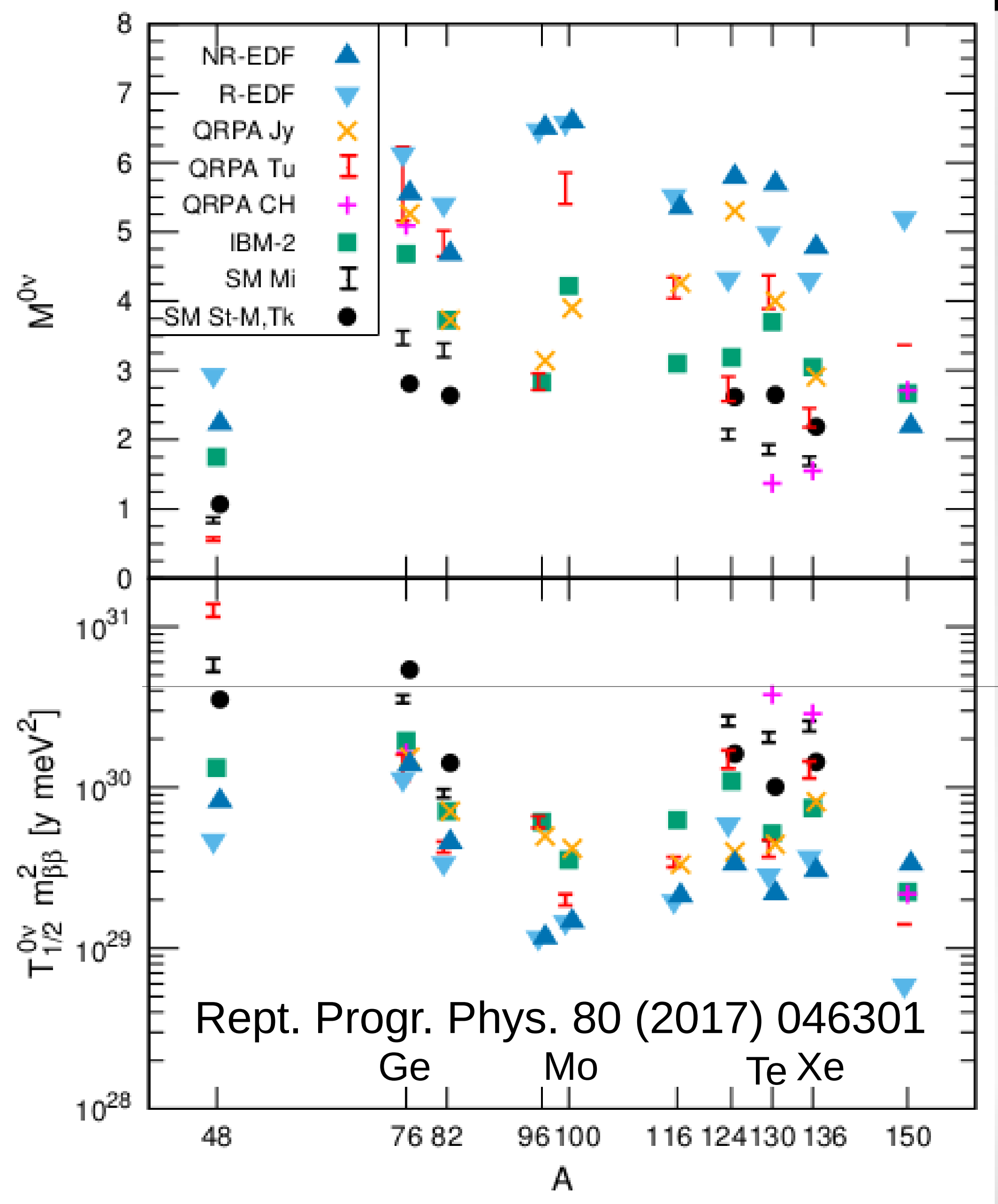
Experiment observes $N^{0\nu} = \ln 2 \, \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \,/\, T_{1/2}$ and $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

Experimental sensitivity

$$T_{1/2}(90\%\,CL) > \begin{cases} \frac{\ln 2}{2.3}\,\frac{N_A}{A}\, a \cdot \epsilon \cdot M \cdot t & \text{for } N^{bkg} = 0 \\ \frac{\ln 2}{1.64}\,\frac{N_A}{A}\, a \cdot \epsilon \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$$

M = mass of detector
t = measurement time
A = isotope mass per mole
N_A= Avogadro constant
a = fraction of 0νββ isotope
ε = detection efficiency
B = background index in units cnt/(keV kg y)
ΔE = energy resolution = energy window size

Nuclear matrix element calculations



Rept. Progr. Phys. 80 (2017) 046301

variety of NME calculations
typically factor ~2-3 variation
→ factor ~4-9 in $T_{1/2}$

10^{28} yr for 20 meV
→ ~0.3 decays per ‘t yr’ exposure

Background reduction

signal: 2 e^- with $\Sigma E_{kin} = Q_{\beta\beta}$ → energy well known and 'localized' E deposition

backgrounds:

muons (cosmic rays) → go underground, deeper → lower flux

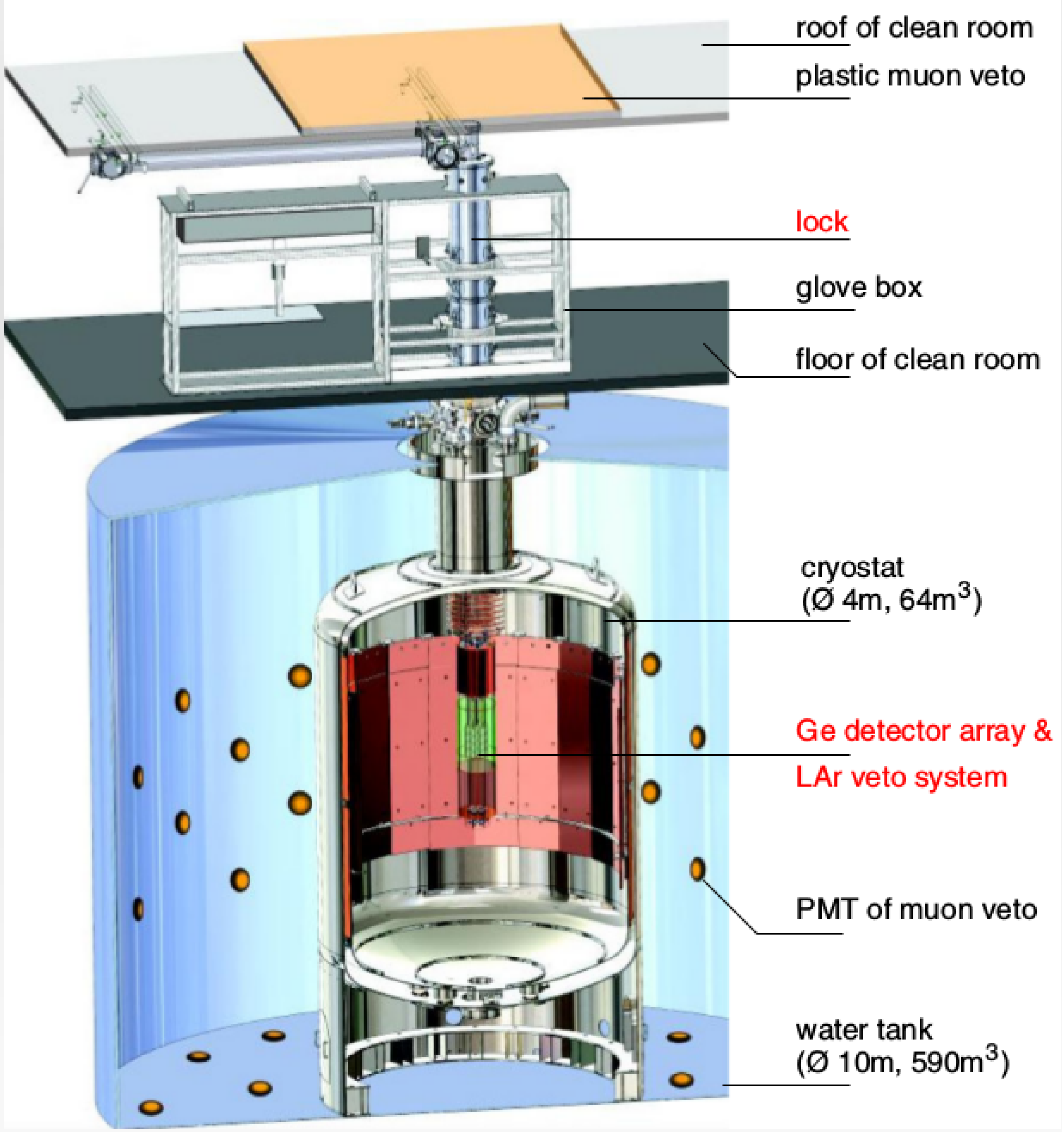
neutrons (muons or (α,n) reactions) → shielding by low Z material, delayed coincidence

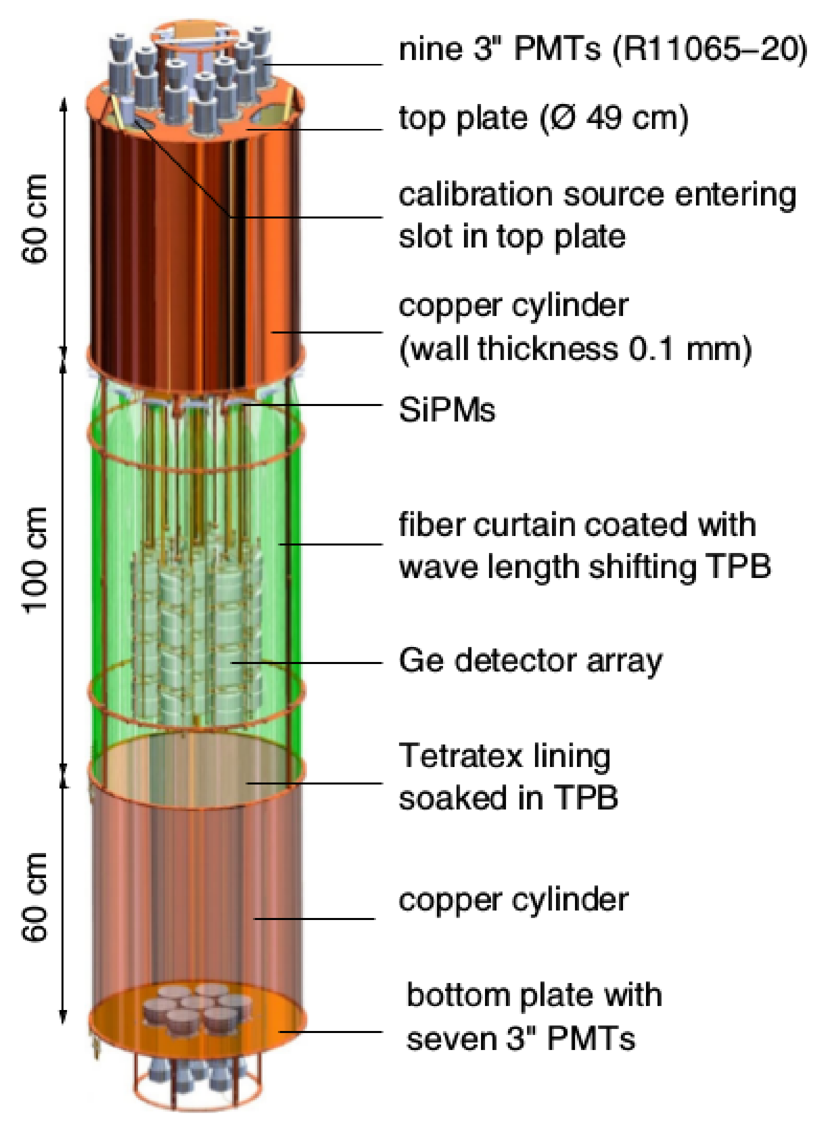
γ (U/Th decay chain) → use "clean" material (screening)
shield with clean material like liquid scintillator or water or LAr
particle ID (single ionization vs. multiple Compton, …)
only "active material" (see additional energy depositions)

e/α (surface events) → fiducial volume,
particle ID

$2\nu\beta\beta$ (allowed decay) → energy resolution

GERDA: Ge in LAr @ Gran Sasso



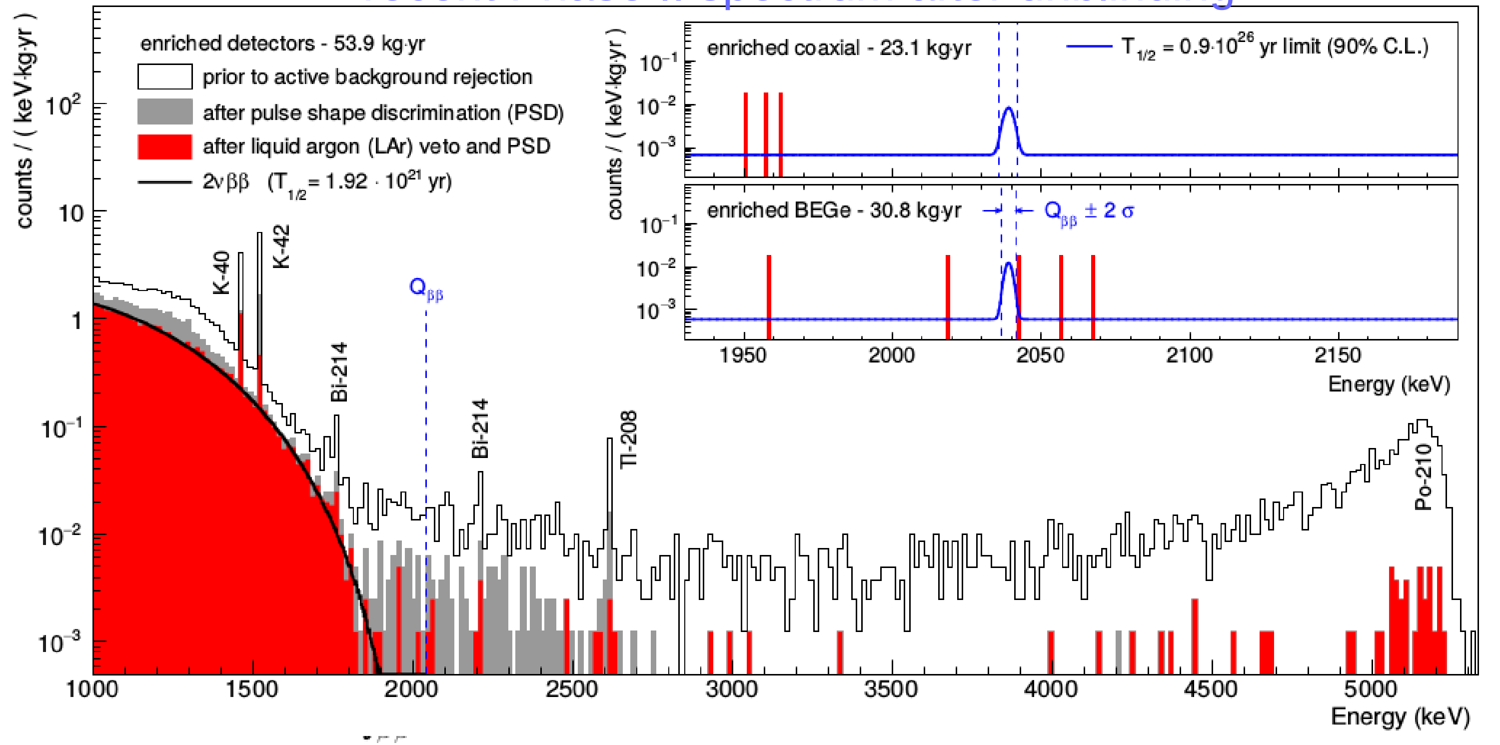


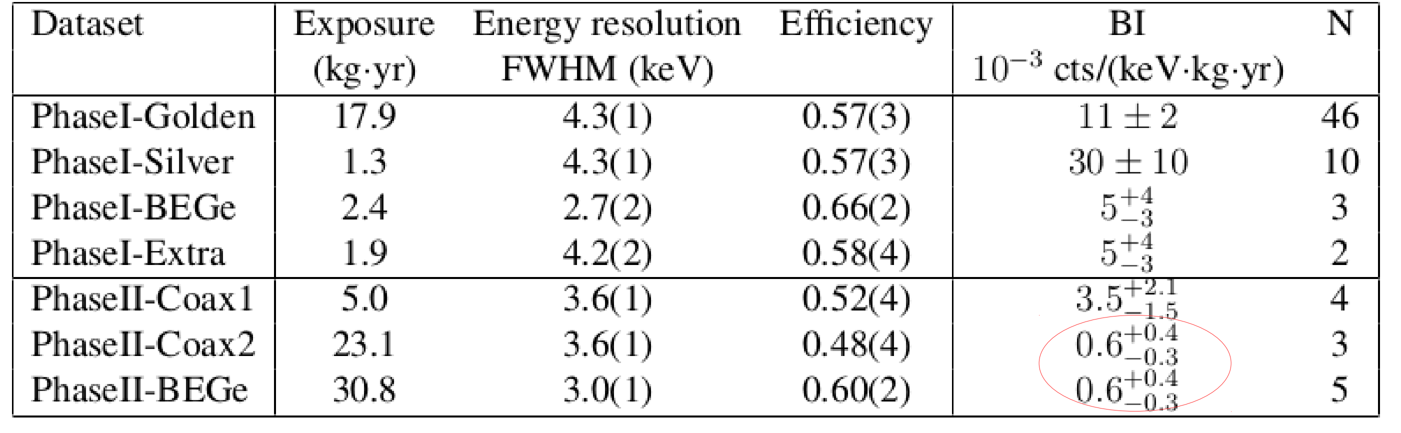
EPJ C78 (2018) 388

Phase I / II data taking since 2013 / 2015

GERDA latest result 2018

recent Phase II spectrum after unblinding





Dataset	Exposure (kg·yr)	Energy resolution FWHM (keV)	Efficiency	BI 10^{-3} cts/(keV·kg·yr)	N
PhaseI-Golden	17.9	4.3(1)	0.57(3)	11 ± 2	46
PhaseI-Silver	1.3	4.3(1)	0.57(3)	30 ± 10	10
PhaseI-BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}	3
PhaseI-Extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}	2
PhaseII-Coax1	5.0	3.6(1)	0.52(4)	$3.5^{+2.1}_{-1.5}$	4
PhaseII-Coax2	23.1	3.6(1)	0.48(4)	$0.6^{+0.4}_{-0.3}$	3
PhaseII-BEGe	30.8	3.0(1)	0.60(2)	$0.6^{+0.4}_{-0.3}$	5

Neutrino 2018:

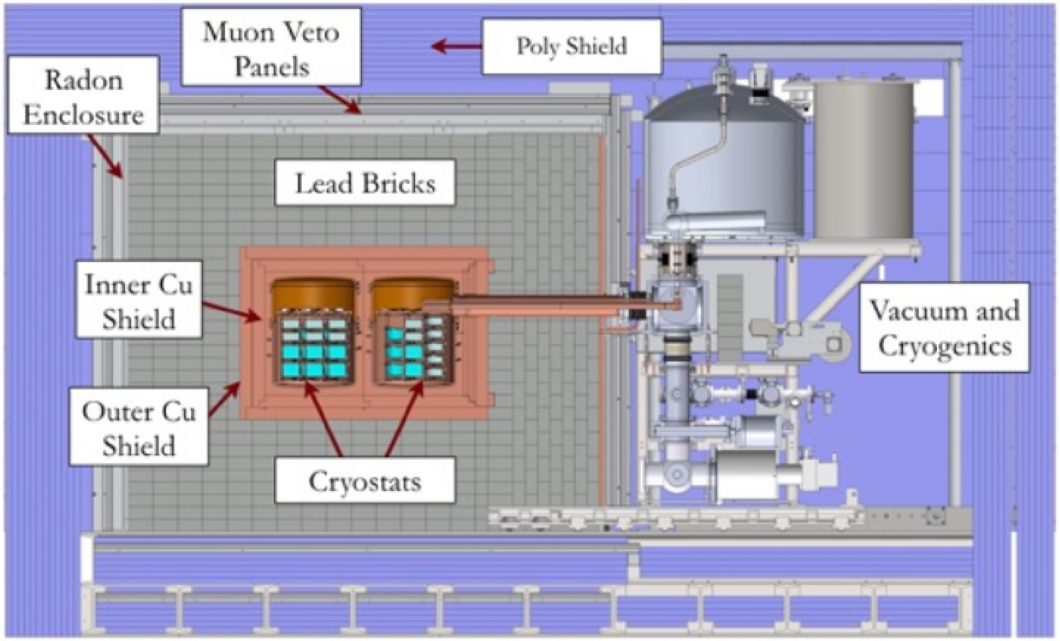
Frequentist:
90% C.L. limit
0.9×10^{26} yr
sensitivity
1.1×10^{26} yr

Bayesian:
90% C.I. limit
0.8×10^{26} yr
sensitivity
0.8×10^{26} yr

Friday morning: nuclear physics

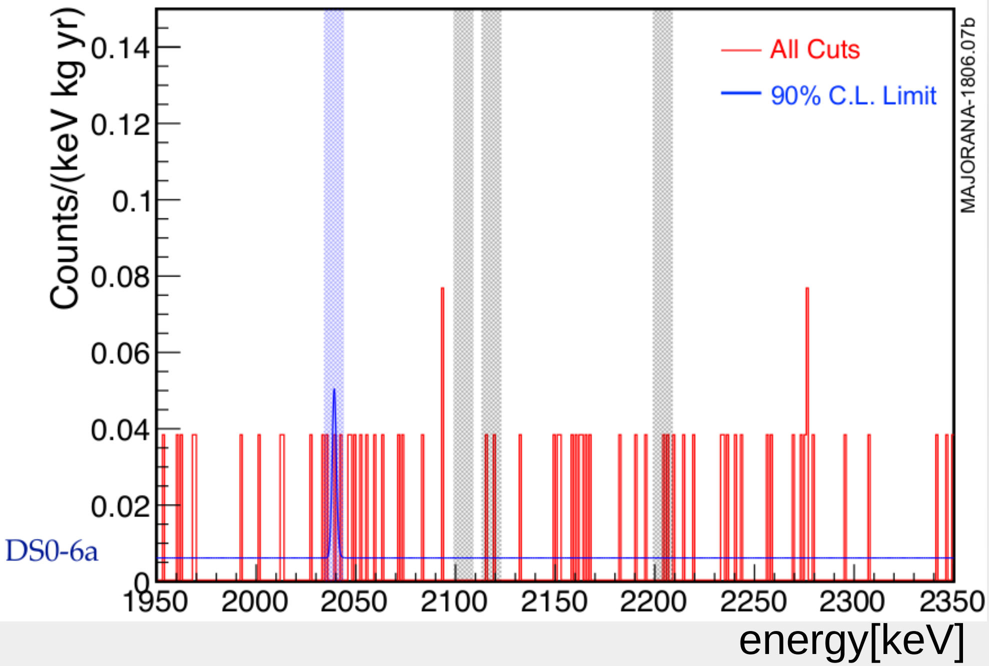
BI * 100 kg yr * FWHM < 1
→ ‘background -free’

Majorana Demonstrator: ^{76}Ge in Cu shield



[N. Abgrall et al. Adv. High Energy Phys **2014**, 365432 (2014)]

preliminary new analysis (NEUTRINO18)



'conventional' shielding with Cu+Pb
self-made electroformed Cu
low background electronics, cables, ...

35 PPC with 88% ^{76}Ge (30 kg)
23 BEGe (natural, 14 kg)

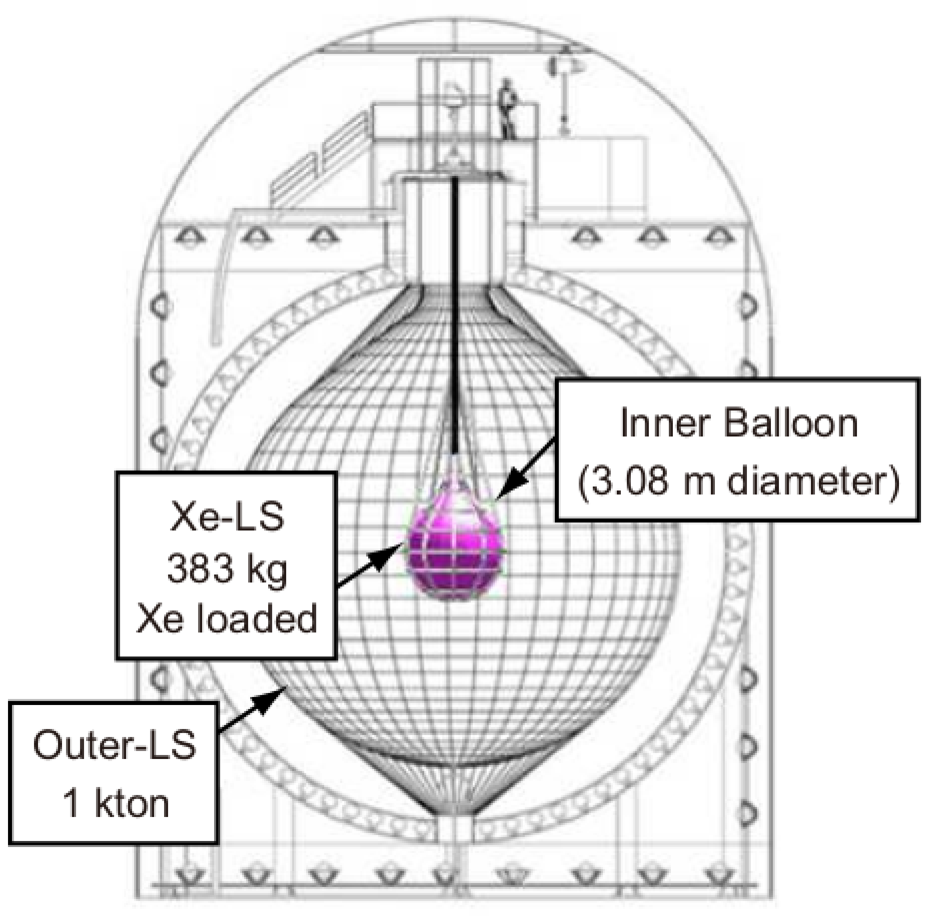
first result PRL 120 (2018) 132502

- 26 kg yr (active mass),
- FWHM ~ 2.5 keV → best in field
- background ~5 cnt/(keV t_{active} yr)

90% C.L. limit $T_{1/2} > 2.7 \times 10^{25}$ yr

sensitivity 4.8×10^{25} yr

Kamland-Zen: ^{136}Xe in scintillator

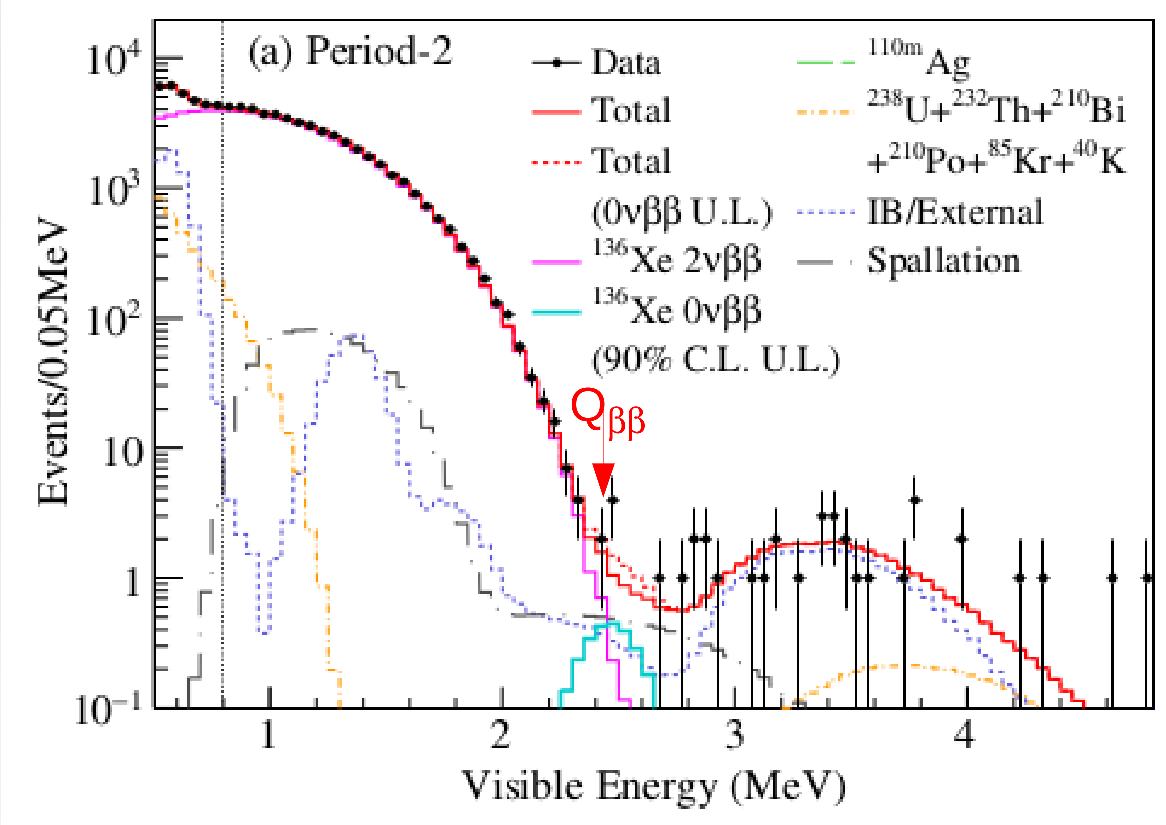


Inner Balloon
(3.08 m diameter)

Xe-LS
383 kg
Xe loaded

Outer-LS
1 kton

PRL 117 082503 (2016)



FWHM ~ 240 keV, background ~ 0.4 cnt/(keV t_{Xe} yr) in centeral 1m Ø, total exposure ~ 600 kg yr

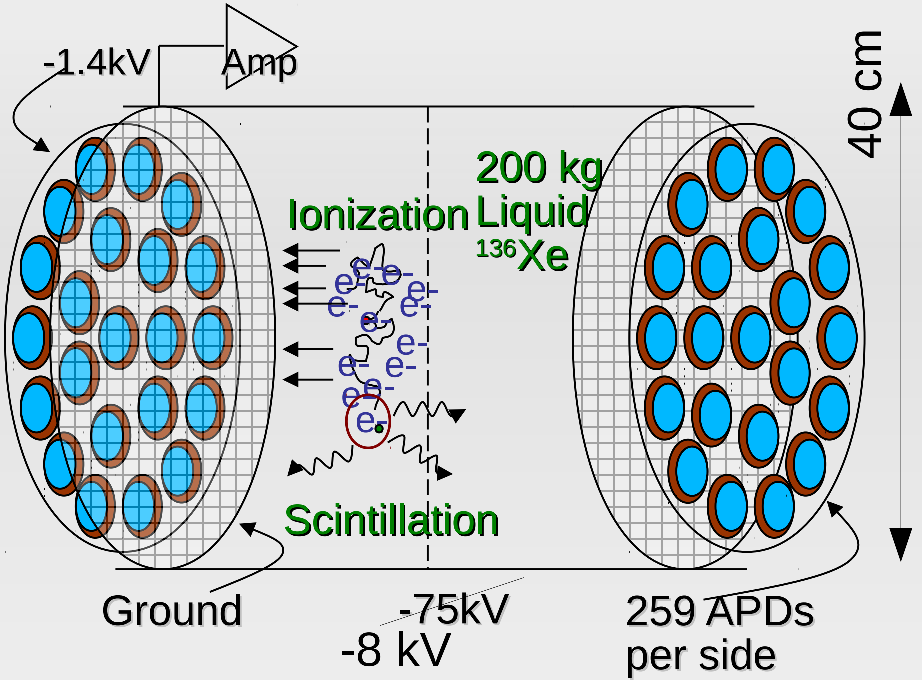
$T^{0\nu}_{1/2} > 10.7\cdot 10^{25}$ yr (90% C.L.)   sensitivity ~5.6 10^{25} yr

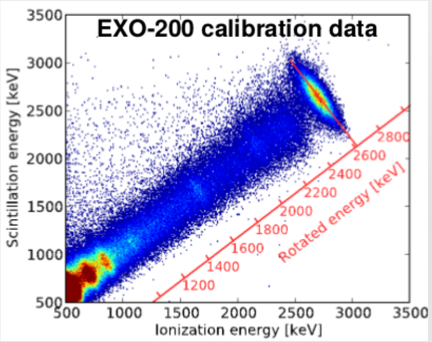
Kamland Zen 800: larger & cleaner balloon, 750 kg, restart 2018, sensitivity 5 x 10^{26} yr

future Kamland Zen2: more light, 1000 kg

(Wednesday morning: Neutrino physics 3)

EXO-200: liquid ^{136}Xe TPC

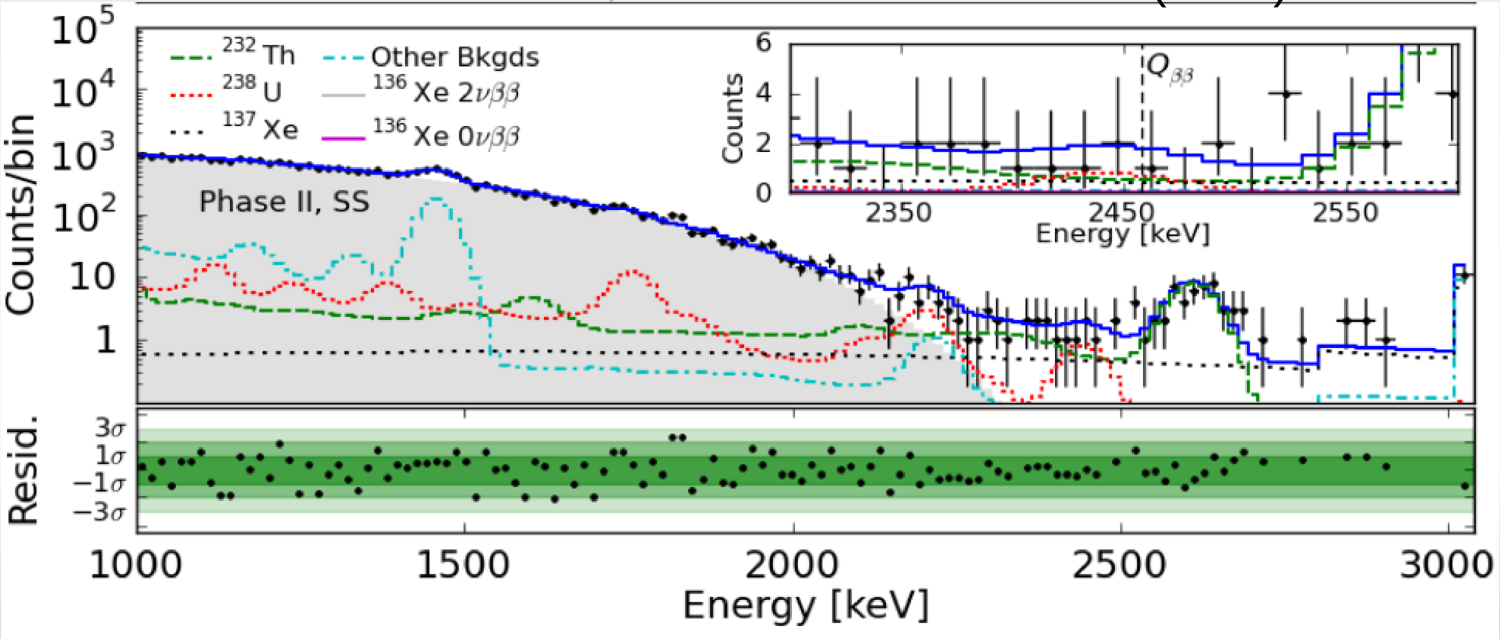




FWHM ~70 keV @ $Q_{\beta\beta}$

1.5 σ excess
90% C.L. limit $T_{1/2} > 1.8 \times 10^{25}$ yr
sensitivity 3.8×10^{25} yr

PRL 120 (2018) 072701

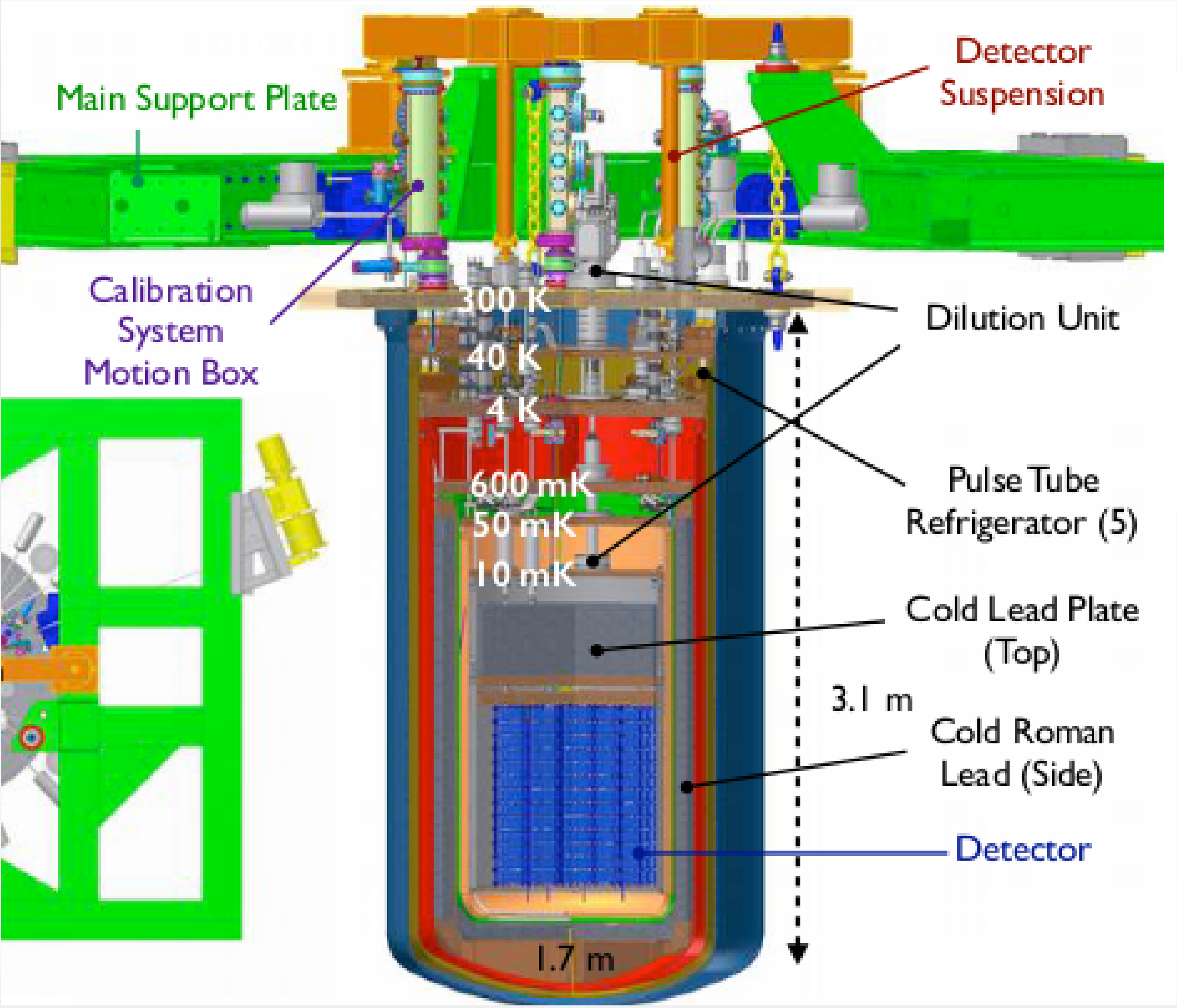


background
~0.1 c/(FWHM kg yr)

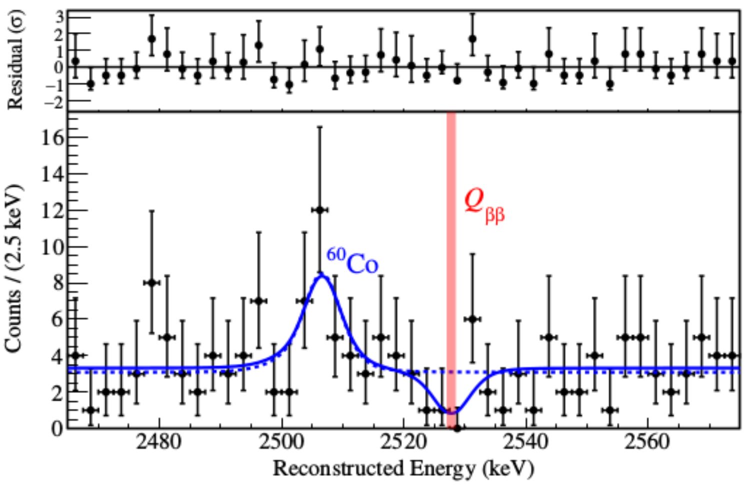
see Wednesday morning (Neutrino physics 3)

stop data taking in 2018

CUORE: TeO_2 crystals at 10 mK



PRL 120 (2018) 132501

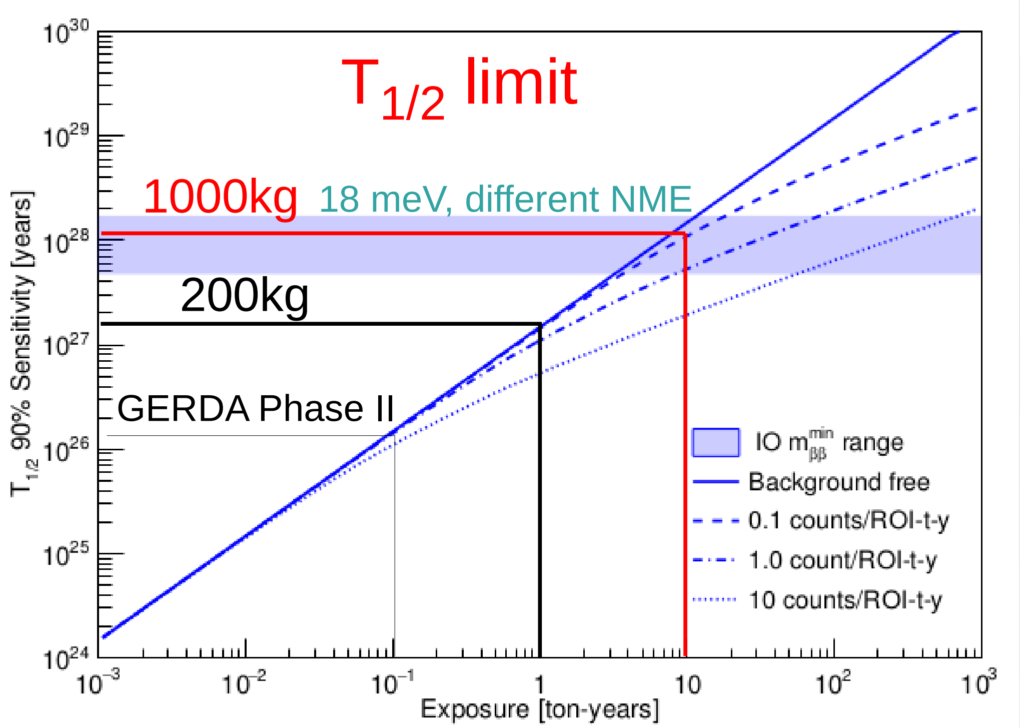


data taking start in 2017
206 kg ^{130}Te in 740 kg of crystals
almost all of 988 channels working!
avg FWHM 7.7 keV

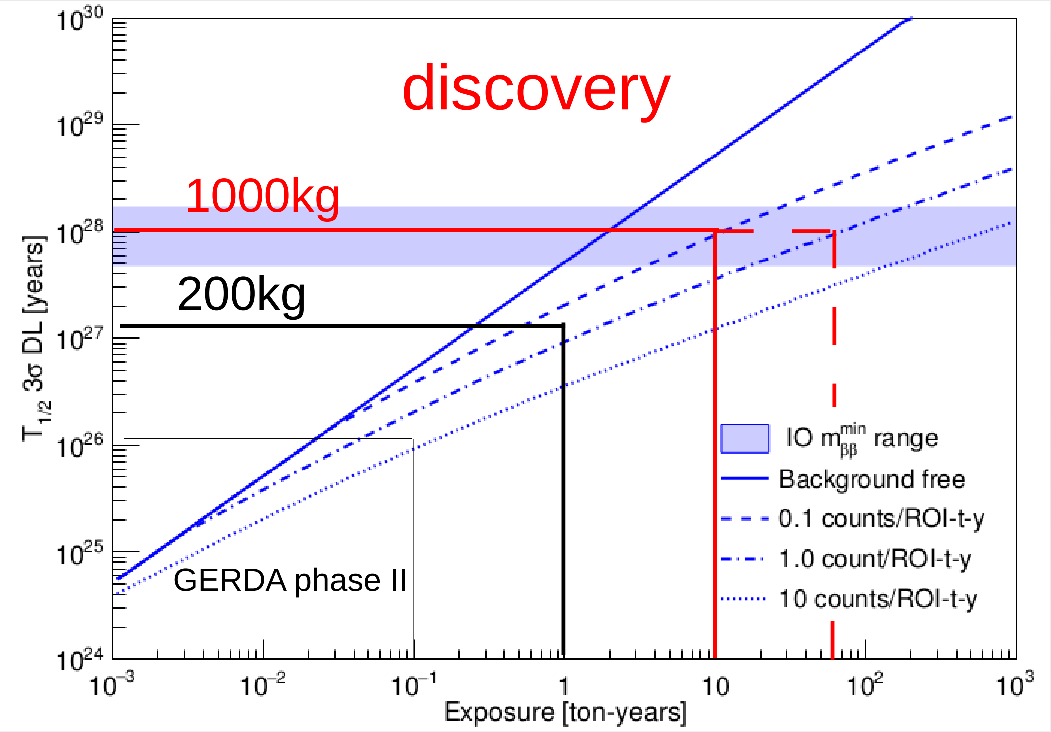
no signal (strong underfluctuation)

90% limit $T_{1/2} > 1.5 \times 10^{25}$ yr
sensitivity 0.7×10^{25} yr

Discovery vs limit setting



as example for ^{76}Ge



discovery: 50% chance for a 3σ signal

low background important
especially for discovery!

Comparison (some) experiments

		mass [kg]* (total/FV)	FWHM [keV]	background& [cnt/t yr FWHM]	$T_{1/2}$ limit sens. [10^{25} yr] final	m_{ee} limit, worst NME [meV] (g_A=1.27)	
Gerda II	Ge	35/27	3	4	15	190	running
MajoranaD	Ge	30/24	2.5	15	15	190	
EXO-200	Xe	170/80	88	140	6	220	
Kamland-Z	Xe	383/88 750/??	240	90 ?	6 50	220 80	
Cuore	Te	600/206	5	370	9	210	
NEXT-100	Xe	100/80	17	30	6	220	constr.
AMoRe I/(II)	Mo	5/ (200)			2/(100)	300/(40)	
SNO+	Te	2340/260	190	60	17	150	
LEGEND200	Ge	200/160	2.5	1	100	75	
KamL2-Zen	Xe	1000/??	170			50	future
nEXO	Xe	5000/4000	58	5	900	18	
CUPID-Mo	Mo		5	<0.2	200	30	
LEGEND-1k	Ge	1000/800	2.5	<0.2	1000	24	

* total= element mass, FV= 0νββ isotope mass in fiducial volume (incl enrichment fraction)

& kg of 0νββ isotope in active volume and divided by 0νββ efficiency

Summary

(my) strong prejudice: $0\nu\beta\beta$ exists, $\Delta L=2$ process, possibly our only observable ΔL

$T_{1/2}$ unknown (depending on BSM physics ...), discovery can be 'around the corner'

currently many new results – more experiments start data taking soon
no signal – $T_{1/2}$ sensitivities reach now 10^{26} yr

future will (hopefully) have a few experiments with sensitivities 10^{27} – 10^{28} yr
→ reach $m_{\beta\beta} < 20$ meV (using worst case NME, unquenched g_A)

which technology is good for 10^{28} yr and will be funded?